

## MULTIWAVELENGTH CASCADED RAMAN RESONATOR

### PRIORITY APPLICATION

This application claims priority from a provisional U.S. patent  
5 application, Serial Number 60/275,261, filed on March 12, 2001, hereby  
incorporated by reference.

### FIELD OF THE INVENTION

The present invention relates to Raman resonators.

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### BACKGROUND OF THE INVENTION

Raman amplifiers and resonators are known in the field of optical  
communications. These devices rely on the Raman effect. When light is  
transmitted through matter, part of the light is scattered in random directions. A  
15 small part of the scattered light has frequencies removed from the frequency of  
the incident beam by quantities equal to vibration frequencies of the material  
scattering system. This small part is called Raman scattering. If the initial beam  
is sufficiently intense and monochromatic, a threshold can be reached beyond  
which light at the Raman frequencies may be amplified, generally exhibiting the  
20 characteristics of stimulated emission. This stimulated emission is commonly  
referred to as the stimulated Raman scattering.

One device employing the Raman effect is a cascaded Raman resonator  
("CRR"). Generally, a CRR receives radiation from a source pump at a  
particular wavelength,  $\lambda_{\text{pump}}$ , and shifts the radiation through one or more steps  
25 to a desired output wavelength,  $\lambda_{\text{out}}$ , where  $\lambda_{\text{out}}$  is greater  $\lambda_{\text{pump}}$ . While various  
types of CRRs exist, one type currently being examined is a fiber-based CRR,  
which shifts the wavelength of the pump light in an optical fiber. Fiber-based

CRRs are capable of providing higher power in a single mode fiber than single mode semiconductor diodes. To date, fiber-based CRRs have been used for remote pumping of Er-doped fiber amplifiers, and as pumps for Raman amplifiers.

5 In an optical fiber, the gain curve from the Raman effect is relatively broad, yet not particularly flat over a wide frequency range. To obtain a flat gain curve, a Raman amplifier may be pumped using several different wavelengths, each triggering the Raman effect. The gain profile of such a Raman amplifier is effectively the superposition of the gain of each of the  
10 individual pumps, in addition to the interaction between the pumps. Presently, these pumps have been realized by multiplexing a number of semiconductor laser diodes or CRRs together. Multiplexing schemes, however, add additional cost to the overall device and place wavelength and polarization limitations on the semiconductor diodes. The power required from each single wavelength device  
15 is modest when compared to the total power that a CRR is capable of producing. However, the total power in all of the wavelengths is comparable to that obtainable from a CRR. It has therefore been advantageous to turn the large amount of power available at a single wavelength of a CRR into power at multiple wavelengths.

20 One practical solution for making a multiple wavelength cascaded Raman resonator ("MWCRR") has been to variably distribute power over the output wavelengths. This approach has been disadvantageous because the tolerances imposed by a system on the wavelength power ratio of a MWCRR are tighter than the possible manufacturing tolerances. Moreover, the specifications  
25 imposed by the system also depend on the final assembly of the system. The performance of the system, consequently, may be enhanced by dynamically controlling the wavelength power ratio and, hence, the shape of the gain curve.

As such, a need remains for the ability to control the wavelength power ratio of a MWCRR.

## **SUMMARY OF THE INVENTION**

5 We have invented a method for controlling the relative wavelength power distribution in a Raman device, such as, for example, a MWCRR. In accordance with the present invention, an optical device employs at least one output coupler having a reflectivity which may be independently varied or tuned to compensate or achieve a desired power distribution. The reflectivity of the  
10 output coupler may be modified using various means, including, for example, applying a non-uniform stress, heat or a voltage/current.

In one example of the present invention, a Raman device, such as, for example, a MWCRR, comprises at least one set of optical gratings coupled with at least a first and a second output coupler for controlling the relative  
15 wavelength power distribution. Here, each output coupler has a reflectivity which varies in response to the application of a non-uniform stress, heat or a voltage/current.

## **BRIEF DESCRIPTION OF THE DRAWINGS**

20 The present invention will be better understood from reading the following description of non-limiting embodiments, with reference to the attached drawings, wherein below:

**FIG. 1(a)** is a schematic diagram of the quantum mechanical behavior of Raman scattering, while **FIG. 1(b)**, is a graphical illustration of the  
25 Raman gain spectrum in an optical fiber;

**FIG. 2(a)** is a schematic view of a known cascaded Raman resonator, while **FIG. 2(b)** is a graphical illustration of the reflectivity versus wavelength for another known cascaded Raman resonator of **FIG. 2(a)**;

**FIG. 3** is a schematic view of an embodiment of the present invention;

**FIG. 4** is a schematic view of a feature of the present invention;

**FIG. 5** is a graphical illustration of the reflectivity versus wavelength of the feature depicted in **FIG. 4**;

5 **FIG. 6** is a graphical illustration of the in-band optical power versus wavelength of an example of the embodiment of **FIG. 3**;

**FIG. 7** is a schematic view of another embodiment of the present invention; and

10 **FIG. 8** is a schematic view of yet another embodiment of the present invention.

It should be emphasized that the drawings of the instant application are not to scale but are merely representations of the invention, which may be determined by one of skill in the art by examination of the information contained herein.

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### **DETAILED DESCRIPTION**

Referring to **FIG. 1(a)**, a schematic diagram of the quantum mechanical behavior of Raman scattering is illustrated. Raman scattering is a process by which light incident on a medium is converted to light at a lower frequency than the incident light. A pump photon,  $\nu_p$ , may be excited up to a virtual level (e.g., non-resonant state). The pump photon decays to a lower energy level emitting a photon,  $\nu_s$ , relatively quickly during this process. The difference in this energy translates into molecular vibrations having a number of levels. It is these levels that determine the shape of a Raman gain curve.

25 Referring to **FIG. 1(b)**, a graphical illustration of the Raman gain spectrum in an optical fiber is shown. Here, the normalized gain in an optical fiber is depicted as a function of the frequency shift created by the Raman effect.

Due to the amorphous nature of silica fibers, the Raman gain spectrum is relatively broad. Because the pump photon is excited to a virtual level, the Raman gain can occur for a pump source at any wavelength. In Ge-doped silica fibers, the peak of this gain will occur at a frequency about 13 THz away from the frequency of the input light.

Referring to FIG. 2(a), a schematic view of a known cascaded Raman resonator (“CRR”) 10 is shown. CRR 10 may be employed in conjunction with an optical multiplexer, for example, to provide optical gain over a number of wavelengths. More particularly, CRR 10 comprises an optical source 15, such as a pump laser (e.g., Ytterbium-doped cladding pumped fiber laser lasing in the 1060-1200 nm region), for generating continuous wave (“CW”) optical radiation at a first wavelength  $\lambda_1$ . Coupled with source 15 are one or more individual input gratings 20. Each of the one or more input gratings 20 has a reflectivity. In one example, the reflectivity of each input grating 20 is between about eighty (80%) percent and one-hundred (100%) percent — though other operable reflectivities are contemplated herein — and is commonly referred to as a “high reflector.” Input gratings 20 are written into a first end of an optical waveguide 25, such as a Raman gain medium (e.g., Raman fiber). Alternatively, input gratings 20 may be spliced onto the first end of an optical waveguide 25. As shown, each grating from input gratings set 20 are centered at second, third, fourth, fifth and sixth wavelengths  $\lambda_2$ ,  $\lambda_3$ ,  $\lambda_4$ ,  $\lambda_5$ , and  $\lambda_6$ .

CRR 10 also comprises one or more output gratings 30. Output gratings 30 are written into or spliced onto a second end of optical waveguide 25. Output gratings 30 are coupled with input gratings 20 by an intermediate section of optical waveguide 25. Much like input gratings 20, each grating of output gratings 30 comprises a high reflector. Each high reflector of output gratings 30 is centered at an individual wavelength  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ ,  $\lambda_4$ , and  $\lambda_5$ .

Coupled with output gratings set 30 is at least one output coupler 35. Output coupler 35 comprises at least one grating centered at sixth wavelength  $\lambda_6$ . Unlike input and output gratings, 20 and 30, the grating of output coupler 35 has a relatively lesser reflectivity. In one example, output coupler 35 has a reflectivity of less than about eighty (80%) percent. In so doing, output coupler 35 allows optical radiation at sixth wavelength  $\lambda_6$  to propagate out from CRR 10.

Operationally, CRR 10 receives CW optical radiation at first wavelength  $\lambda_1$  from optical source 15. The CW optical radiation at first wavelength  $\lambda_1$  propagates through input gratings 20, and is converted within optical waveguide 25 to second wavelength,  $\lambda_2$ , and from second wavelength,  $\lambda_2$ , to third wavelength,  $\lambda_2$ , and from third wavelength,  $\lambda_3$ , to fourth wavelength,  $\lambda_4$ , and from fourth wavelength,  $\lambda_4$ , to fifth wavelength,  $\lambda_5$ , and from fifth wavelength,  $\lambda_5$ , to sixth wavelength,  $\lambda_6$ , by means of the Raman effect. Input gratings 20, here, improve the efficiency of CRR 10 by reflecting forward any backscattered light back into optical waveguide 25. Any optical radiation propagating through output gratings 30 at first, second, third, fourth and fifth wavelengths,  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ ,  $\lambda_4$ , and  $\lambda_5$ , are reflected back through optical waveguide 25 by one of the high reflectors centered at wavelengths  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ ,  $\lambda_4$ , and  $\lambda_5$  in output gratings 30. Consequently, optical radiation at first, second, third, fourth, and fifth wavelengths —  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ ,  $\lambda_4$ ,  $\lambda_5$  — emanates from optical waveguide 25 reflected back to optical waveguide 25 by one of the gratings of output gratings 30. By this design, optical radiation having a wavelength other than sixth wavelength,  $\lambda_6$ , is nominally blocked from escaping a cavity forming CRR 10. Consequently, input and output gratings, 20 and 30, effectively convert the wavelength (e.g.,  $\lambda_1$ ) of the optical radiation from optical source 15 to a higher wavelength (e.g.,  $\lambda_6$ ). This higher wavelength (e.g.,  $\lambda_6$ ) is dependent on

selecting the center wavelength of the high reflectors of input and output gratings, 20 and 30, as well as the center wavelength of output coupler 35.

Referring to FIG. 2(b), a graphical illustration of the reflectivity versus wavelength for a known multiple wavelength CRR ("MWCRR") design is illustrated. In this known MWCRR approach, the wavelength power ratio of the MWCRR is controlled by shifting the center wavelength of the output coupler. This deliberate shifting is effectuated by misaligning the cavity of the MWCRR at a particular wavelength. In so doing, the efficiency of the cavity at the particular wavelength is reduced, thereby lowering the power emitted at the particular wavelength. The results of such an implementation are characterized in the graphical illustration of FIG. 2(b).

Referring to FIG. 3, a schematic view of an embodiment of the present invention is illustrated. Here, a solution is realized for wavelength power distribution control in a MWCRR, for example, without shifting the center wavelength of the output coupler(s). We have recognized that the reflectivity of the output coupler may be controlled, for example, by writing a chirped or unchirped grating into an optical waveguide, such as a Raman optical fiber, of the MWCRR. The optical waveguide in which these gratings are written into or spliced onto may also be coated with a metal. Consequently, the peak reflectivity of these gratings may be decreased by applying a stress, heat (e.g., uniform or non-uniform) or an electrical voltage/current to the coating of the metal of the particular chirped gratings. Likewise, upon removing the stress, heat or electrical voltage/current, the peak reflectivity of these gratings may be relatively increased. As such, the amount of light that may be extracted from the cavity of an MWCRR at a predetermined wavelength may be controlled in accordance with the principles of the present embodiment.

More particularly, the schematic view of FIG. 3 shows a multiple wavelength CRR ("MWCRR") 100 employing the principles of the present

embodiment. MWCRR 100 comprises a pump optical source 105, such as a cladding pumped fiber laser, for generating continuous wave ("CW") optical radiation at a first wavelength  $\lambda_1$  (e.g., 1100 nm). Coupled with pump optical source 105 are a first and second set of input gratings, 110 and 115. Each of the

5 one or more gratings in both sets of input gratings, 110 and 115, may be chirped or unchirped and realized by a high reflector. In one example, the reflectivity of each grating in both sets of input gratings, 110 and 115, is between about eighty (80%) percent and one-hundred (100%) percent — though other operable reflectivities are contemplated herein. Both sets of input gratings may be written

10 into or spliced onto a first end of an optical waveguide 120, such as a Raman gain medium (e.g., optical fiber). Unlike CRR 10 of FIG. 2(a), the first set of input gratings 110 have been included because of their feedback properties to allow lasing in MWCRR 100. Each grating in both sets of input gratings, 110 and 115, are centered at a second, third, fourth, fifth, sixth, seventh and eighth

15 wavelength  $\lambda_2$  (e.g., 1153 nm),  $\lambda_3$  (e.g., 1211 nm),  $\lambda_4$  (e.g., 1275 nm),  $\lambda_5$  (e.g., 1347 nm),  $\lambda_6$  (e.g., 1425 nm),  $\lambda_7$  (e.g., 1455 nm), and  $\lambda_8$  (e.g., 1480 nm).

MWCRR 100 also comprises one or more output gratings 125. Output gratings 125 are written into or spliced onto a second end of optical waveguide 120. Output gratings 125 are coupled with both sets of input gratings, 110 and

20 115, by an intermediate section of optical waveguide 120. Each grating of output gratings 125 comprises a high reflector. Furthermore, output gratings 125 are centered at the second wavelength,  $\lambda_2$  (e.g., 1153 nm), third wavelength,  $\lambda_3$  (e.g., 1211 nm), fourth wavelength,  $\lambda_4$  (e.g., 1275 nm), and fifth wavelength,  $\lambda_5$  (e.g., 1347 nm).

25 Coupled with output gratings 125 and written into or spliced onto further along the second end of optical waveguide 120 are a number of adjustable output couplers 130. It should be apparent to skilled artisans that alternative



configurations may also be operative. For example, output couplers 130 may also be positioned in between optical waveguide 120 and output gratings 125.

Each adjustable output coupler 130 comprises an element having variable reflectivity centered at the sixth wavelength,  $\lambda_6$  (e.g., 1425 nm), the seventh wavelength,  $\lambda_7$  (e.g., 1455 nm), and the eighth wavelength,  $\lambda_8$  (e.g., 1480 nm). In one example, the element within each adjustable output coupler 130 is realized by a chirped or unchirped grating. The reflectivity of each adjustable output coupler 130 is controlled by an individual control system 135. In one example, each control system 135 is realized by a stressing or heating source, or, alternatively, an electrical power source for generating a voltage or current, to modify the reflectivity of its respective adjustable output coupler 130. Each control system 135 modifies the percentage of optical radiation propagation transmitted through its respective adjustable output coupler 130, and therefore the reflectivity of the respective adjustable output coupler 130. Consequently, the amount of optical radiation propagating from the cavity of MWCRR 100 at particularly desirable wavelengths is now controllable. As such, the wavelength power ratio and the shape of the gain curve of MWCRR 100 may be dynamically controlled.

Referring to FIG. 4, a schematic view of a feature of the present invention is illustrated. More particularly, FIG. 4 shows one example of an adjustable output coupler 150, which may be used in MWCRR 100 of FIG. 3. Adjustable output coupler 150 comprises an optical fiber 155, such as, for example, a Raman gain medium (e.g., Raman fiber), having a standard coating 175. Written into or spliced onto optical fiber 155 is a grating 170. Grating 170 may be chirped or unchirped. Surrounding grating 170 is temperature responsive tapered metal coating 160, in contrast with standard coating 175. Metal coating 160 is coupled with a power source 180 for increasing the

temperature of grating 170. The increase in the temperature of grating 170 corresponds with the amount of tapered metal at a given point along metal coating 160 in contact with grating 170, as well as the amount of an electrical current applied thereto. The peak reflectivity of grating 170 may be decreased  
5 by applying an electrical voltage/current to metal coating 160 surrounding grating 170. Upon removing the electrical voltage/current from metal coating 160, the peak reflectivity of these gratings may be relatively increased. It should be apparent to skilled artisans that various voltage/current levels generated by power source 180 will correspondingly vary the temperature of grating 170, and  
10 thusly, its peak reflectivity. Consequently, the peak reflectivity of grating 170 may be changed by applying stress or heat. In one example, the stress or heat applied to grating 170 by power source 180 is non-uniform.

Referring to FIG. 5, a graphical illustration of the reflectivity versus wavelength ( $\lambda$ ) of an exemplary adjustable output coupler, such as coupler 150  
15 of FIG. 4, is shown.

Referring to FIG. 6, a graphical illustration of the in-band optical power versus wavelength ( $\lambda$ ) of an exemplary MWCRR, such as MWCRR 100 of FIG. 3, is shown. From this graphical illustration, as the voltage applied to an adjustable output coupler centered at the eighth wavelength,  $\lambda_8$ , of 1480 nm is  
20 increased, the output power at that wavelength decreases. Consequently, it should be apparent to skilled artisans that similar results may be obtained by changing the voltage applied to adjustable output couplers centered at the sixth or seventh wavelengths,  $\lambda_6$  or  $\lambda_7$ , of 1425 nm or 1455 nm, respectively.

Referring to FIG. 7, a schematic view of another embodiment of the  
25 present invention is illustrated. Here, an optical apparatus 200 is shown for varying the intensity of optical radiation for a single wavelength over a number of output lines. More particularly, optical apparatus 200 comprises an optical

source **205**, such as a pump laser, for generating continuous wave ("CW") optical radiation at a first wavelength  $\lambda_0$ . The CW optical radiation from optical source **205** is divided by a splitter **207** into  $N$  number of lines (**210<sub>1</sub>**, **210<sub>2</sub>** through **210<sub>N</sub>**), where  $N$  is greater than or equal to two.

5 Each line in optical apparatus **200** comprises a high reflector (**215<sub>1</sub>**, **215<sub>2</sub>** through **215<sub>N</sub>**), coupled with an adjustable output coupler (**225<sub>1</sub>**, **225<sub>2</sub>** through **225<sub>N</sub>**) by means of an optical waveguide (**220<sub>1</sub>**, **220<sub>2</sub>** through **220<sub>N</sub>**), such as a Raman optical fiber. Each adjustable output coupler is centered around the same individual wavelength (e.g.,  $\lambda_1$ ). Alternatively, each adjustable output coupler  
10 may be centered around individual wavelengths (e.g.,  $\lambda_1$ ,  $\lambda_2$  through  $\lambda_N$ ) — depending on the purpose of the dividing the optical radiation. The output from each adjustable output coupler is fed into an optical amplifier (**230<sub>1</sub>**, **230<sub>2</sub>** through **230<sub>N</sub>**) to generate  $N$  number of outputs (**OUTPUT<sub>1</sub>**, **OUTPUT<sub>2</sub>** through **OUTPUT<sub>N</sub>**). Consequently, the power level (e.g., intensity) of each output may be adjusted,  
15 as such, by varying each adjustable output coupler. As a result, the outputs (**OUTPUT<sub>1</sub>**, **OUTPUT<sub>2</sub>** through **OUTPUT<sub>N</sub>**) may have individual power levels or intensities ( $I_1$ ,  $I_2$  through  $I_N$ ). Moreover, the adjusted power level of the outputs may be centered around the same wavelength ( $\lambda_1$ ), or individual wavelengths (e.g.,  $\lambda_1$ ,  $\lambda_2$  through  $\lambda_N$ ).

20 Referring to **FIG. 8**, a schematic view of another embodiment of the present invention is illustrated. Here, an optical apparatus **300** for selecting the power distribution of at least two wavelengths. More particularly, optical apparatus **300** comprises an optical source **305**, such as a pump laser, for generating continuous wave ("CW") optical radiation at a first wavelength  $\lambda_0$ .  
25 The CW optical radiation from optical source **305** is divided by a splitter **307** into  $N$  number of lines (**310<sub>1</sub>**, **310<sub>2</sub>** through **310<sub>N</sub>**) where  $N$  is greater than or equal to two.

Each line in optical apparatus **300** comprises a high reflector (**315<sub>1</sub>**, **315<sub>2</sub>** through **315<sub>N</sub>**), coupled with an adjustable output coupler (**325<sub>1</sub>**, **325<sub>2</sub>** through **325<sub>N</sub>**) by means of an optical waveguide (**320<sub>1</sub>**, **320<sub>2</sub>** through **320<sub>N</sub>**), such as a Raman optical fiber. Since each adjustable output coupler is centered around an individual wavelength ( $\lambda_1$ ,  $\lambda_2$  through  $\lambda_N$ ). The output lines (**330<sub>1</sub>**, **330<sub>2</sub>** through **330<sub>N</sub>**) from each adjustable output coupler are each fed to a combiner **335** for combining the optical radiation at each individual wavelength ( $\lambda_1$ ,  $\lambda_2$  and  $\lambda_N$ ) into a single line output (**OUTPUT**). Consequently, power level of each of the individual wavelengths ( $\lambda_1$ ,  $\lambda_2$  through  $\lambda_N$ ) may be adjusted within the single line output (**OUTPUT**) by varying one or more of the adjustable output couplers (**325<sub>1</sub>**, **325<sub>2</sub>** through **325<sub>N</sub>**).

While the particular invention has been described with reference to illustrative embodiments, this description is not meant to be construed in a limiting sense. It is understood that although the present invention has been described, various modifications of the illustrative embodiments, as well as additional embodiments of the invention, will be apparent to one of ordinary skill in the art upon reference to this description without departing from the spirit of the invention, as recited in the claims appended hereto. It is therefore contemplated that the appended claims will cover any such modifications or embodiments as fall within the true scope of the invention.